Journal of Cleaner Production 226 (2019) 357–368

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Energy intensity and embodied energy flow in Australia: An input-output analysis

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ARTICLE INFO

Article history:
Received 1 November 2018
Received in revised form
4 March 2019
Accepted 29 March 2019
Available online 1 April 2019

Keywords:
Energy intensity
Embodied energy flow
Input-output analysis
Time-series analysis
Structural decomposition analysis
Australia

ABSTRACT

Decoupling energy use from economic growth is critical for improving energy productivity and mitigating climate change. Input-output databases have been increasingly utilised for consumption-based energy accounting, and for exploring both the direct and indirect influence of energy use. This study performed an environmentally-extended input-output analysis of energy use in Australia from 2006 to 2015 to investigate the total energy intensity of industry sectors, and the embodied energy flow from sources of energy use to the final consumption of commodities. Between 2006 and 2015, the national direct energy intensity reduced by an average of 2% per annum. Nearly all industry sectoral groups reduced their total energy intensity because of direct energy intensity reduction from other or within industry sectoral groups. The difference between the embodied energy use in the import and the export had widened, making Australia a greater net importer of embodied energy with significant outsourcing of direct energy use and associated greenhouse gas emissions. Despite a slight reduction in per capita direct household energy use (3%), the per capita indirect energy use embodied in household commodity consumption increased by 7%. As indirect household energy use is more than three times direct household energy use, improving end use energy efficiency should also consider the embodied energy in commodities. Structural decomposition analysis shows that for the studied period, population growth and per capita demand for imported commodities are two major contributors for the increased total embodied energy in Australia.

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1. Introduction

Decoupling energy use from economic growth is critical for climate change mitigation and improving energy productivity (International Energy Agency, 2017). A growing body of work has contributed to that by exploring industry energy intensity and consumption-driven embodied energy use on national, regional and global scales.

Energy intensity is a widely-used indicator to reflect the energy efficiency of an economy. It is often measured as total primary energy demand per unit of gross domestic product (International Energy Agency, 2017). Most studies have explored national energy intensity (Shahiduzzaman and Alam, 2013; Voigt et al., 2014) or industry energy intensity (Chen and Chen, 2015; Tiwari, 2000). Quite often, decomposition analysis was used to explore drivers of influence. For instance, Voigt et al. (2014) used a global multi-regional input-output database (WIOD) to conduct an index decomposition analysis (IDA) to understand whether structural change or technology improvement is the major driver behind the changes in national energy intensities in 40 countries between 1995 and 2009. Using the same database, Löschel et al. (2015) performed a similar IDA to explore the drivers for an overall decline in the aggregated energy intensity of the EU27 countries. Zeng et al. (2014) conducted a structural decomposition analysis (SDA) of energy intensity of China to show that sectoral energy efficiency improvement was a key driver for an overall decline in energy intensity between 1997 and 2007.

Recent years have seen an increasing use of input-output (IO) analysis to quantify consumption-based embodied energy use/energy footprint (Owen et al., 2017) and energy embodied in trade at

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https://doi.org/10.1016/j.jclepro.2019.03.322
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different scales (Chen et al., 2018). IO analysis can model embodied energy flows based on sectoral intermediate exchanges (Chen and Chen, 2015). The approach has been quite extensively applied to quantify embodied energy use for individual sectors (Chang et al., 2010; Lenzen and Dey, 2000), sub-national embodied energy flow (Hong et al., 2016; Zhang and Lahr, 2014), and embodied energy in trade (Liu et al., 2010; Moreau and Vuille, 2018). Aggregate embodied energy and carbon intensity can also be derived from the demand perspective using different forms of IO models (Su and Ang, 2015, 2017).

Under the IO framework, there are also different analytical techniques such as structural decomposition analysis (SDA) and structural path analysis (SPA). SDA can quantify the impacts of different driving factors on aggregate energy/emissions indicators within the IO framework (Chen and Chen, 2017; Wang et al., 2017). The driver decomposition of energy intensity and embodied energy use using SDA has been performed on national, regional and global levels (Lan et al., 2016; Xie, 2014). Another IO-based technique SPA can identify the top contributing paths to the embodied impacts such as energy (Owen et al., 2018) and carbon emissions (Shao et al., 2018).

Building on some of these earlier efforts, this paper contributes to the literature concerning economic energy intensity and embodied energy of final consumption of commodities. First, existing literature has been mostly focusing on the direct industry or national energy intensity (Löschel et al., 2015; Shahiduzzaman and Alam, 2013; Voigt et al., 2014), with relatively few studies on the total industry energy intensity (including both direct and indirect) and its trend. Input-output analysis has the ability to capture spill-over effects of energy productivity gains in one industry on another (Gowdy, 1992). For a given sector, its total energy intensity is useful for evaluating the environmental pressure caused by its economic activities (Wu and Chen, 2017). Second, national-scale studies tend to use the domestic technology assumption, which could be potentially misleading if a country has substantial imports. By combining a detailed national supply-and-use table with a global input-output database, this study addressed this limitation to better quantify the embodied energy flow. Third, existing energy input-output analysis for Australia are not recent (Gowdy, 1992; Lenzen, 1998, 2001), sectoral specific (Crawford, 2005; Palmer, 2017), region specific (Baynes et al., 2011; Lenzen et al., 2004a) or being part of some global studies (Akizu-Gardoki et al., 2018; Lan et al., 2016). This study contributes an up-to-date national-scale energy input-output analysis for Australia, with structural decomposition analysis and structural path analysis.

The objective of this study is to examine the changes in total industry energy intensity and embodied energy flow (from both domestic and overseas sources) in Australia between 2006 and 2015 using environmentally-extended input-output analysis. Structural decomposition analysis was performed to understand the drivers behind the changes in the embodied energy, while structural path analysis was used to identify key contributing paths for the embodied energy. The implications of this study for energy input-output analysis are also discussed. The recent development of a cloud-based multi-regional input-output (MRIO) table building platform in Australia has enabled timely and flexible construction of time-series multi-regional input-output table (Lenzen et al., 2014, 2017b). In addition, the Australian Bureau of Statistics has been publishing a set of time-series energy account (Australian Bureau of Statistics, 2018a) that is consistent with the system of national accounts, including the national input-output table. This time-series dataset minimises the uncertainties in energy data allocation process to align with the national input-output table, which would otherwise need.

2. Methods and data

2.1. Structure of the MRIO table

Fig. 1 shows the structure of the integrated MRIO table used in this study. The details of its development are described in Section 2.7. The intermediate transaction matrix consists of 110 Australian industries (Aus - Industry), 110 Australian commodities (Aus - Commodity) and 26 industry sectors from the rest of the world (RoW). The Australian section of the matrix is in a supply-and-use table (SUT) framework. In a SUT framework, the use table shows the sales of commodities to industries, and the supply table shows the value of commodities produced by industries (Wiedmann, 2017).

In addition to the intermediate transaction matrix, there are the value added block (V), the net energy use extension (F), the final demand block (y) and the total output (x). GDP is the sum of the first four row elements in the V block (i.e., compensation of employees, gross operating surplus & mixed income, taxes less subsidies on products, other taxes less subsidies on production). For each region, the final demand block (y) has six elements – final consumption expenditure (households, government), gross fixed capital formation (private, public enterprise, general government), and changes in inventory. The total output (x) is the sum of the intermediate consumption and final demand.

2.2. Quantifying direct industry energy intensity

In this study, for a given industry, its direct energy intensity is defined as its net energy use per its gross domestic product. It is a widely-used indicator to reflect the energy efficiency of an economy. For all Australian industries, their direct energy intensities ($EI_{direct,\,Aus}$) are:

$$EI_{direct,\,Aus} = F_{Aus-ind}/GDP_{Aus} \tag{1}$$

where

- $F_{Aus-ind}$ is a row vector of net energy use used by each Australian industry (PJ) (the Australian section of the F block in Fig. 1).
- GDP_{Aus} is a row vector of the gross domestic product for each Australian industry ($) (the Australian section of the first four row elements in the V block in Fig. 1).
- / denotes element-wise division.

2.3. Quantifying total industry energy intensity

Total industry energy intensity is defined as the total industry embodied energy use (direct + indirect) per industry gross domestic product. In order to derive the total industry energy intensity, standard input-output calculus was applied (Miller and Blair, 2009). The total impact multiplier is defined as (in this study, it represents the total energy multiplier m) (Wiedmann, 2017):

$$m = f(I-A)^{-1} = fL \tag{2}$$

$$f = F\hat{x}^{-1} \tag{3}$$

where

- m is a row vector of the total energy multiplier (PJ/$) with n elements (where n is the total number of industries and commodities in a national supply-and-use table framework, plus the

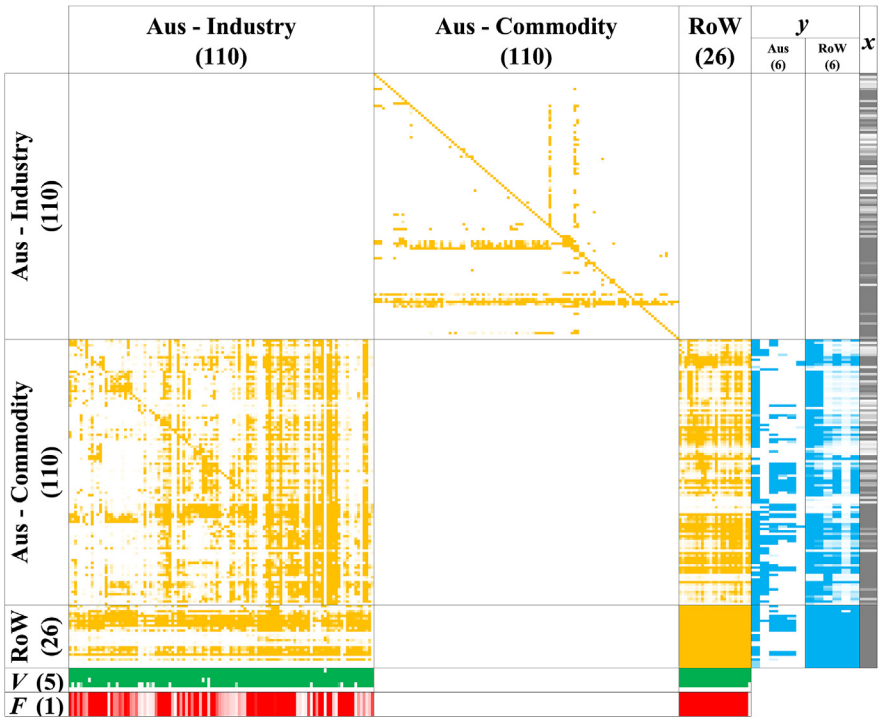

Fig. 1. Structure of the integrated MRIO table. *V* is the value added block. *F* is the net energy use extension. *y* is the final demand block. *x* is the total output. The number of row/column in each block is shown in the bracket.

number of overseas industries.). In this study, n is 110 + 110 + 26 = 246 (Fig. 1). This row vector (m) consists of three sets of multipliers - 110 Australian industry multipliers ($m_{Aus-\ ind}$) are at the industry block, 110 Australian commodity multipliers ($m_{Aus-\ com}$) are at the commodity block, while 26 import multipliers (m_{row}) are at the RoW block.

- f is a row vector of the direct energy multiplier (PJ/$).
- F is a row vector of net energy use (PJ) with n elements (where the Australian industry block has the net energy use for each Australian industry, with zeros in the Australian commodity block, and the RoW block has the net energy use for each overseas industry (Fig. 1)).
- I is an $n \times n$ identity matrix.
- A is an $n \times n$ technology coefficient matrix (obtained from column-wise division of the $n \times n$ intermediate transaction matrix by the total output vector x).
- L is the standard Leontief Inverse ($L = f(I-A)^{-1}$).
- $\widehat{x}^{-1}$ is an inverse matrix of diagonalised total output x.

With the total energy multipliers derived from equation (2), the total industry energy intensity ($EI_{total,\ Aus}$) can be obtained by multiplying the industry multipliers element-wisely with total industry outputs, and then dividing element-wisely by industry gross domestic product:

$$EI_{total,Aus} = (m_{Aus-ind} \times x_{Aus-ind})/GDP_{Aus} \tag{4}$$

where

- $m_{Aus-ind}$ is a row vector of the total energy multiplier for each Australian industry (PJ/$).
- $x_{Aus-ind}$ is a row vector of the total output for each Australian industry ($).
- GDP_{Aus} is a row vector of the gross domestic product for each Australian industry ($).
- $\times$ denotes element-wise multiplication.
- / denotes element-wise division.

2.4. Quantifying embodied energy

The embodied energy in the final domestic consumption (EE) can be quantified by multiplying the total energy multipliers (m) with the final demand columns (y in Fig. 1).

$$EE = \sum_{c=1}^{6} m \times y_c \tag{5}$$

where

- m is a vector of the total energy multiplier obtained from equation (2) (PJ/$).
- y_c is a vector of the c th column of final demand elements ($). For Australia, the six columns include final consumption expenditure (households, government), gross fixed capital formation (private, public enterprise, general government), and changes in inventory (Fig. 1).
- $\times$ denotes element-wise multiplication.

2.5. Structural decomposition analysis of embodied energy

Structural decomposition analysis (SDA) has been widely used to quantify the impacts of different driving factors on aggregate energy/emissions indicators within the input-output framework (Wang et al., 2017). Dietzenbacher and Los (D&L) method and the logarithmic mean divisa index (LMDI) are two common methods for SDA (Su and Ang, 2012). Both methods can give ideal decomposition without any unexplained residuals. As the number of

decomposed factors (n) increases in the D&L method, it can become hard to formulate the decomposition (i.e., the number of decomposition equations is equal to $n!$). In this study, the number of factors in the initial decomposition is four, and D&L method was used (no preference between D&L method and LDMI method when the number of factors is four or fewer (Su and Ang, 2012)). The embodied energy (EE) is:

$$EE = fLYp \tag{6}$$

where

- f is the direct energy multiplier (PJ/$). It represents industry energy intensity on per unit of gross industry output basis (i.e., different from the per unit GDP basis).
- L is the standard Leontief Inverse. It represents the economic structure.
- Y is the per capita final demand in Australia.
- p is the population in Australia.

Through SDA, the change in embodied energy (EE) can be expressed as changes of four effects.

$$\Delta EE = f_{effect} + L_{effect} + Y_{effect} + p_{effect} \tag{7}$$

Using D&L method, equation (7) was decomposed into $4! = 24$ equations. Each of these 24 equations have four terms. The mean of the same term across all these 24 equations is the corresponding effect. The full set of decomposition equations and effect equations are included in the Supplementary Material.

By invoking a part of the final demand or a part of the direct energy multiplier, we can further decompose two factors (i.e., direct energy multiplier, per capita final demand) into domestic contribution and overseas contribution. This results in a total of six factors (industry energy intensity (Australia), industry energy intensity (Overseas), economic structure, per capita final demand for domestic commodity, per capita final demand for imported commodity, and population).

2.6. Structural path analysis

Structural path analysis provides a systematic method to identity key supply chains contributing to the embodied environmental impacts for commodities (Lenzen and Crawford, 2009). The total energy multiplier (equation (2)) can be decomposed by expanding the Leontief inverse term $(I-A)^{-1}$, shown in equation (8). The first-order path is from industry j to commodity i (A_{ji}). The second-order path is from commodity/industry j to industry k to commodity i ($A_{jk}A_{ki}$). The third-order path is from industry j to commodity/industry l to industry k to commodity i ($A_{jl}A_{lk}A_{ki}$). The higher-order paths can be extended in the same way. For the Nth order, the number of paths is n^N, where n is the total number of industries and commodities. By isolating and ranking the paths, structural path analysis identifies the more significant paths that contribute to the total embodied energy in Australia.

For a given commodity i,

$$m_i = \sum_{j=1}^{n} \frac{F_j}{x_j}\left(\delta_{ji} + A_{ji} + \sum_{k=1}^{n} A_{jk}A_{ki} + \sum_{l=1}^{n}\sum_{k=1}^{n} A_{jl}A_{lk}A_{ki} + \ldots\right) \tag{8}$$

where

- j, k and l can be either a commodity or an industry depending on the order of the path and the section of the A block (i.e., commodity/industry in the domestic block or industry in the overseas block)
- δ_{ji} is the zero-order direct impact term. If $j = i$, it is equal to one, else equal to zero.
- A is the $n \times n$ technology coefficient matrix. j, k and l are essentially the index terms. Each combination of j, k, l (and higher-order terms) is a path.

2.7. Data sources

2.7.1. Input-output data

A time-series set (2006–2015) of national input-output data in the supply-and-use (SUT) framework (with 110 industries and 110 commodities) was obtained from a cloud-based multi-regional input-output (MRIO) table building platform (the Australian Industrial Ecology Virtual Laboratory (IELab) (Lenzen et al., 2014)). The tables were built based on a number of data sources, including the supply-and-use tables (Australian Bureau of Statistics, 2017c, d), national accounts (Australian Bureau of Statistics, 2017b) and industry financial data (Australian Bureau of Statistics, 2017e) published by the Australian Bureau of Statistics (ABS). A full list of data sources is provided in the Supplementary Material. The industry classification of the SUT tables follows that of the ABS IOIG 2009 classification, except "Electricity Generation" and "Electricity Transmission, Distribution, On Selling and Electricity Market Operation" have been aggregated as "Electricity Supply".

The SUT table from the IElab also has an import block (from the rest of the world), and an export block (to the rest of the world). To account for the upstream impact from overseas and the downstream flow to overseas intermediate consumption and overseas final consumption, the table was integrated with a global input-output database – Eora (Lenzen et al., 2013), following the approach described by Wolfram et al. (2016). Through this integration of national IO tables and global IO tables into MRIO tables, the international feedback effects can be captured (Su and Ang, 2011). A description of the integration approach is also included in the Supplementary Material.

There are five common global MRIO databases – Eora (Lenzen et al., 2013), EXIOBASE (Stadler et al., 2018), GTAP (Peters et al., 2011), OECD ICIO (OECD, 2018) and WIOD (Timmer et al., 2015). At the time of writing, Eora is the only global MRIO database that has the year coverage (2006–2015) and net energy use metric used in this study. The other four global MRIO databases have different limitations – EXIOBASE 3 (1995–2011, net energy supply and gross energy use metrics), GTAP 9 (2004, 2007, 2011, gross energy use metric), OECD ICIO 2018 release (2005–2015, no energy metric); WIOD 2016 release (2000–2014, no energy metric). The major reasons for building a new set of MRIO tables from the IELab instead of directly using the Eora database are i) for a national-scale study, using financial and energy data from national statistics agency is arguably more accurate, and ii) the industry classification used in the MRIO tables from the IELab (unlike that of the Eora) can align well with the industry classification used in the energy extension developed in this study (discussed in the next section).

To compare the results across year, the set of MRIO tables has to be converted from a current price term to a constant price term for a reference year (2015) (Lan et al., 2016). A double-deflation approach was used (i.e., residual adjustment of value added) (Dietzenbacher and Hoen, 1998). Industry-specific deflators were applied. They were derived from the Producer Price Indexes (PPIs) and the International Trade Price Indexes published by the national statistics agency (Australian Bureau of Statistics, 2018c, d). Where a few service-based industries do not have the corresponding PPI, Consumer Price Indexes were used (Australian Bureau of Statistics,

2018b).

2.7.2. Energy data

The domestic energy extension used in this study is based on the Energy Account, Australia (EAA) (Australian Bureau of Statistics, 2018a). The EAA is the national energy statistics published by the ABS. It is one of the environmental-economic accounts produced by the ABS and is therefore consistent with the Australian System of National Accounts, including the national input-output table. The net energy use dataset from the EAA (for 2006 to 2015) was used in this study. The net use perspective avoids the issue of double counting as in the case of using gross energy use account. The original dataset has net energy use (by 19 energy products) for 22 industry sectors and a "conversion and losses" sector (which includes the energy loss from all energy conversion activities). In this study, the energy use in the "conversion and losses" sector was allocated to the corresponding sectors that have energy conversion activities (i.e., mostly in petroleum and chemical products manufacturing sector and electricity supply sector, with some minor conversions also in mining sector, wood, paper, printing manufacturing sector, and iron and steel manufacturing sector). The gross energy use and the gross energy supply dataset from the EAA provides the information to perform this allocation. The detail of the allocation is described in the Supplementary Material.

After allocating the net energy use of the "conversion and losses" sector, the net energy use matrices (19 energy products × 22 industry sectors) for all years were disaggregated into input-output sectoral classification (110 industry sectors). The disaggregation process used energy product expenditure data from the Use table of the ABS input-output table datasets (Australian Bureau of Statistics, 2017d). The tables contain expenditure data of input-output industry groups on 11–16 energy products (depending on the year). The "missing" expenditure data for some energy products have little impact on the overall disaggregation because these energy products are either having relatively small contribution to total energy use (e.g., briquettes, biofuels, wood and wood waste), concentrating in specific sectors (e.g., bagasse only used in sugar industry), or not being used as an energy source in Australia (i.e., uranium).

The resulting net energy use by 110 industry sector vectors (the totals of all energy products) for 2006 to 2015 were used as the environmental extension (the domestic section of *F* in Fig. 1). This net energy use extension was also built as an energy satellite into the cloud-based MRIO platform for energy footprint analysis of commodities. For the net energy use of overseas industries (the rest of the world section of *F* in Fig. 1), the "IEA - Total primary energy supply" extension from the Eora26 for all countries was aggregated into a net energy use vector for the rest of the world.

3. Results and discussion

3.1. Energy intensity and embodied flow in 2015

3.1.1. Direct and indirect industry energy intensity

There are marked differences in the direct and indirect energy intensity of different industry sectoral groups (Fig. 2). The direct energy intensity refers to the direct industry energy use per unit of gross domestic product. The indirect energy intensity reflects the associated energy use of upstream economic activities (both domestic and overseas) contributing to that gross domestic product. Primary (e.g., agriculture, mining) and secondary industries (e.g., petroleum refinery) have higher direct energy intensity, while service-based tertiary industries have lower direct energy intensity.

In 2015, non-ferrous metals manufacturing (predominantly from alumina refinery) had the highest direct energy intensity, though its scale in terms of energy use and GDP contribution is relatively small. Sectors such as food manufacturing, other manufacturing and tertiary industries require a lot of upstream inputs in their supply chains to produce their outputs. The total energy intensities of some tertiary industries (e.g., accommodation,

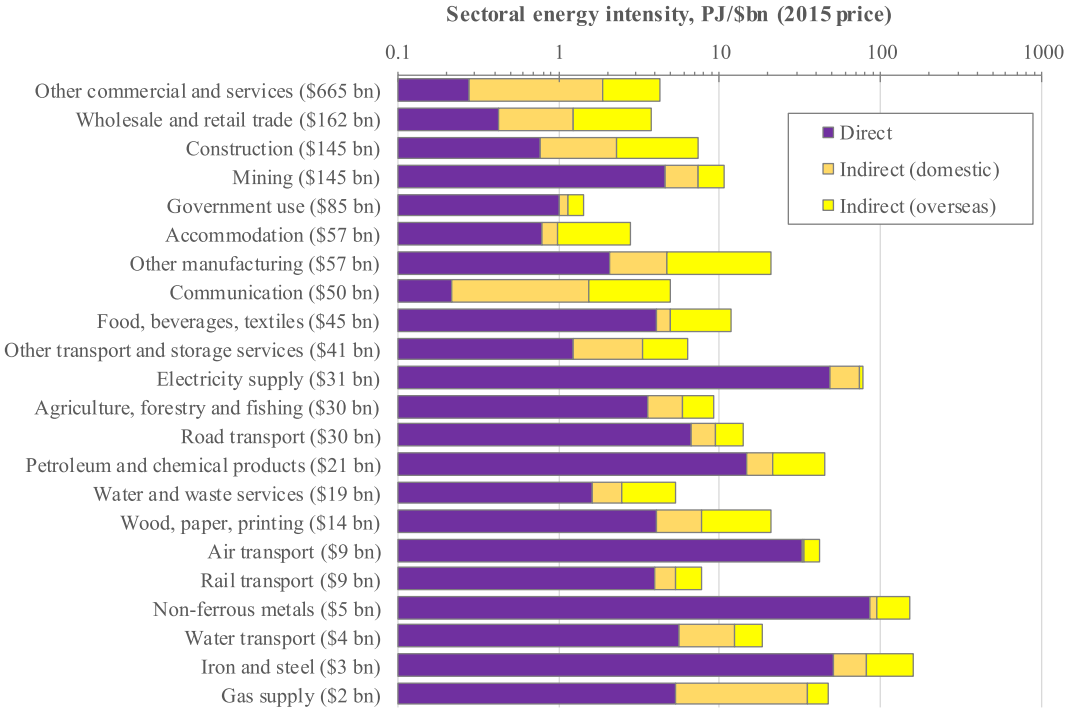

Fig. 2. Total energy intensity in term of direct and indirect energy use (domestic and overseas) by industry sectoral gross domestic product for 22 aggregated industry groups in 2015. Industry sectoral groups are ranked by sectoral gross domestic products (shown in brackets in billion Australian dollars ($bn)). The full 110-industry results are provided in the Supplementary Material.

communication) were similar to the direct energy intensities of some manufacturing industries (e.g., food, beverages and textiles, other manufacturing). It reflects a significant upstream indirect energy impact from these industry groups. Among the industry sectoral groups, over half of them have indirect energy intensity higher than direct energy intensity.

For indirect energy intensity, the results also show that overseas contribution was more significant than domestic contribution. This would indicate most sectors consume a substantial amount of commodities (goods and services) directly or indirectly (through domestic supply chains) from overseas to produce their outputs.

3.1.2. Embodied energy flow

In 2015, 9975 PJ of embodied energy flowed from (a) imported commodities and domestic use of energy products (EP) for domestic industry activity, (b) through intermediate domestic economic activity and direct final consumption of imported commodities, (c) to final domestic consumption (household, government and fixed capital formation) and final overseas consumption (Fig. 3). In addition to that, there was direct household energy use (1286 PJ).

Only approximately half of this total energy (11,261 PJ) was physically used in Australia. Because an industry net energy use view was taken in this analysis, the activity sources of energy use (S) is essentially the net final direct energy use. In other words, most of the energy use in "S - Electricity & gas supply" is the rejected heat, conversion and transmission losses in the electricity generation process, while electricity as an energy product from the electricity supply sector is being consumed in each of the industry activity sources (S). Therefore, the embodied flow from the "I - Electricity & gas supply" to the household is the energy loss in the electricity generation sector being allocated to the household ("I" refers to immediate sectors upstream of final demand).

Downstream sectors such as construction and commercial sectors (within "I - Other") require outputs from upstream primary sectors such as mining and electricity sectors to produce their outputs for the final consumption. For these sectors, their total embodied energy (the "I" layer in Fig. 3) is therefore more than their total direct energy use (the "S" layer in Fig. 3). Direct household energy use was responsible for 15% of total energy use for domestic final consumption. The indirect household energy use through consumption of commodities was over three times (i.e., 56% of total energy use for domestic final consumption) that of direct household energy use.

The results also show that import represents a significant embodied energy inflow into intermediate domestic economic activity. From an embodied energy flow perspective, Australia is a net energy importer with energy embodied in the import being double that of export. This shows a significant outsourcing of energy use, and the associated GHG and air emissions impacts. It should be noted that this is from an energy use perspective. From a physical energy supply perspective, Australia is a significant exporter of energy resources that are being consumed overseas (Department of the Environment and Energy, 2017).

3.2. Energy intensity and embodied energy flow between 2006 and 2015

3.2.1. Direct and indirect industry energy intensity

Between 2006 and 2015, there was an average annual 2% reduction of the national direct energy intensity (the left chart of Fig. 4). The industry sectoral results show that the "other commercial and services" group (41% of the national GDP) was a key contributor to the national energy efficiency improvement (from a

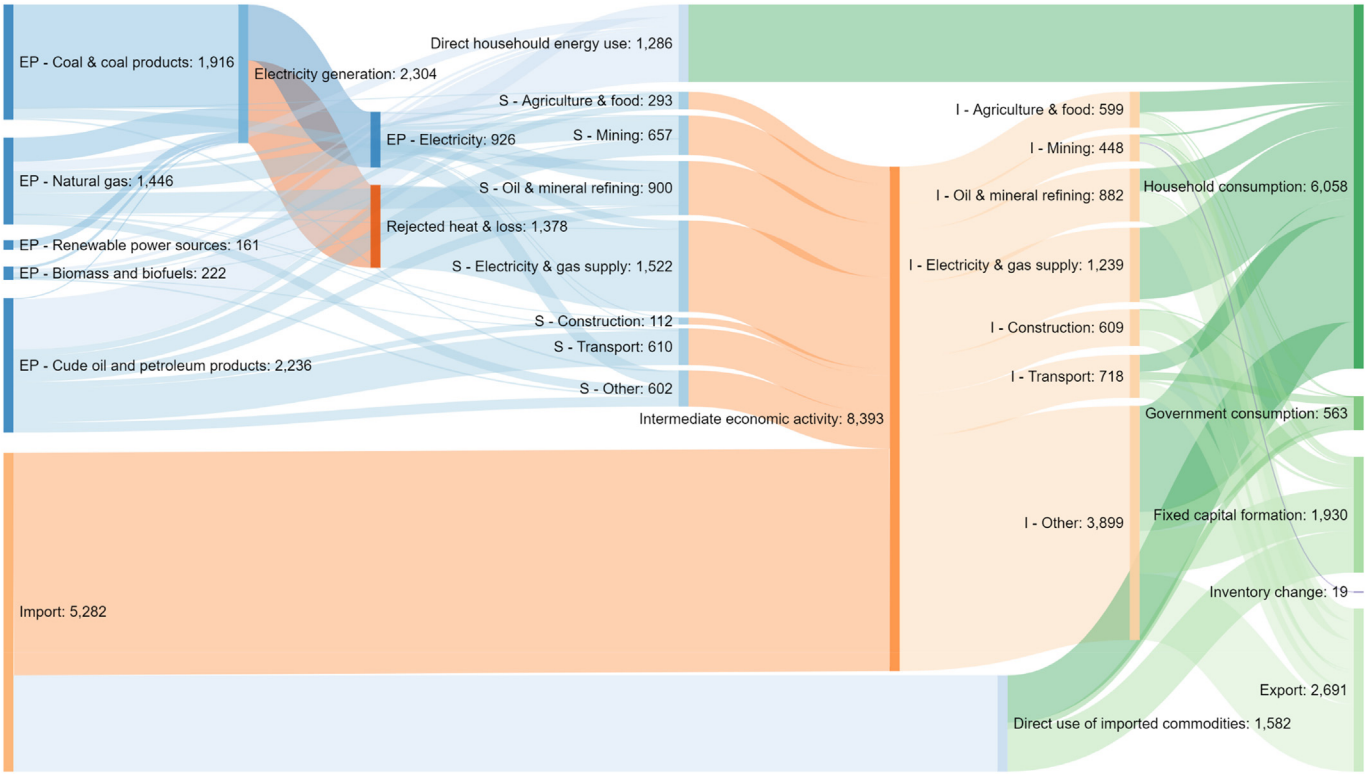
EP - Coal & coal products: 1,916
EP - Natural gas: 1,446
EP - Renewable power sources: 161
EP - Biomass and biofuels: 222
EP - Cude oil and petroleum products: 2,236
Import: 5,282
Electricity generation: 2,304
EP - Electricity: 926
Rejected heat & loss: 1,378
Direct household energy use: 1,286
S - Agriculture & food: 293
S - Mining: 657
S - Oil & mineral refining: 900
S - Electricity & gas supply: 1,522
S - Construction: 112
S - Transport: 610
S - Other: 602
Intermediate economic activity: 8,393
I - Agriculture & food: 599
I - Mining: 448
I - Oil & mineral refining: 882
I - Electricity & gas supply: 1,239
I - Construction: 609
I - Transport: 718
I - Other: 3,899
Direct use of imported commodities: 1,582
Household consumption: 6,058
Government consumption: 563
Fixed capital formation: 1,930
Inventory change: 19
Export: 2,691

Fig. 3. Australian energy flow (PJ) in 2015 from (a) domestic use of energy products (EP) for industry activity sources of energy use (S) and import, to (b) intermediate economic activity and final consumption of imported commodities, to immediate sectors upstream of final demand (I), to (c) final domestic consumption and export.

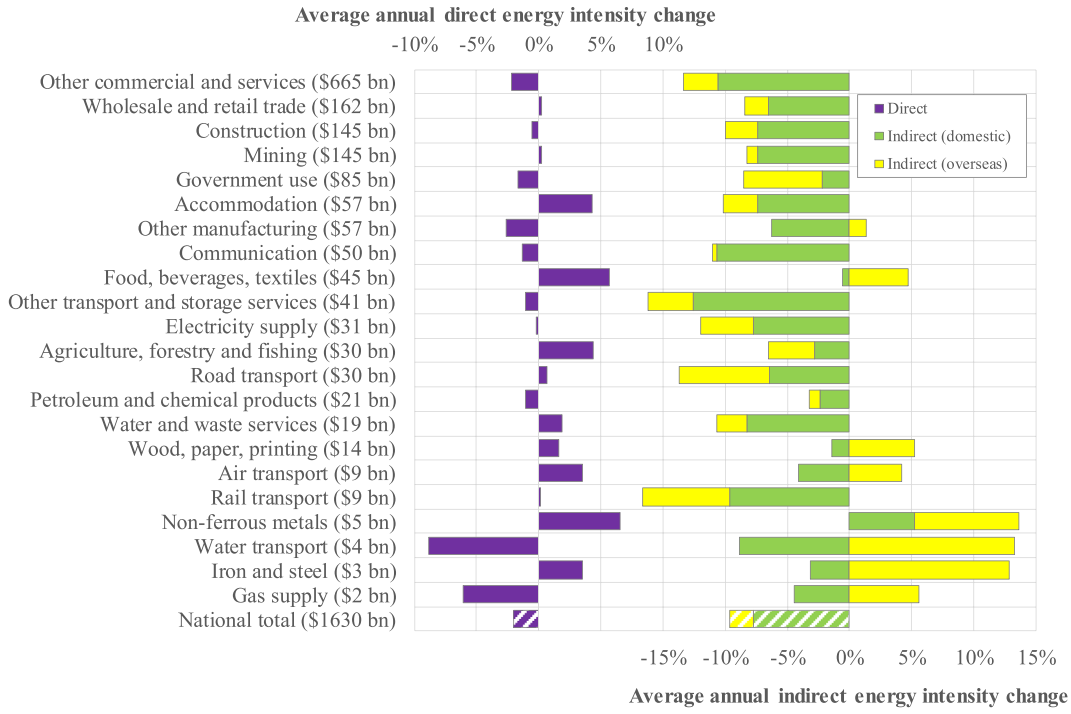
Average annual direct energy intensity change
-10% -5% 0% 5% 10%
Other commercial and services ($665 bn)
Wholesale and retail trade ($162 bn)
Construction ($145 bn)
Mining ($145 bn)
Government use ($85 bn)
Accommodation ($57 bn)
Other manufacturing ($57 bn)
Communication ($50 bn)
Food, beverages, textiles ($45 bn)
Other transport and storage services ($41 bn)
Electricity supply ($31 bn)
Agriculture, forestry and fishing ($30 bn)
Road transport ($30 bn)
Petroleum and chemical products ($21 bn)
Water and waste services ($19 bn)
Wood, paper, printing ($14 bn)
Air transport ($9 bn)
Rail transport ($9 bn)
Non-ferrous metals ($5 bn)
Water transport ($4 bn)
Iron and steel ($3 bn)
Gas supply ($2 bn)
National total ($1630 bn)
Direct
Indirect (domestic)
Indirect (overseas)
-15% -10% -5% 0% 5% 10% 15%
Average annual indirect energy intensity change

Fig. 4. Average annual direct and indirect energy intensity changes for 22 aggregated sectoral groups and national total between 2006 and 2015. Sectoral gross domestic products are shown in brackets in billion Australian dollars.

per unit of GDP perspective). In addition, the electricity supply sector had noticeably reduced its energy intensity. In contrast, the energy intensity of primary industry (e.g., agriculture, forestry and fishing) and manufacturing (e.g., food, beverages, textiles) increased over this period. These sectors collectively accounted for 20% of national GDP.

The magnitude of changes for indirect industry energy intensity (the right chart of Fig. 4) is more substantial than that of direct industry energy intensity. This reflects a significant spill-over and multiplying effect from direct energy intensity changes. Nearly all industry sectoral groups had indirectly gained energy efficiency from direct energy efficiency improvement from other industry sectoral groups (or within their groups).

3.2.2. Embodied energy flow

The direct domestic energy use by industry (F) remained steady between 2006 and 2015, while the embodied energy use (EE) changed considerably (Fig. 5). Despite that the total direct energy use appears relatively stable, there were an increased trend in the mining sectoral group and a reduced trend in the electricity & gas supply sectoral group (driven by the reduced share of coal in the fuel mix for electricity generation). For embodied energy use, all the sectoral groups have seen a growth over the period. There is a clear trend that Australia is becoming a greater net embodied energy importer, which is consistent with literature (Akizu-Gardoki et al., 2018).

Comparing the energy flows in 2006 and 2015 (Fig. 6), the most significant change is that the embodied energy flow from import increased by nearly 40% (from 3811 PJ to 5282 PJ). One of the potential drivers behind this is a distinct increase in final domestic demand for imported commodities (67% increase in embodied energy flow from 944 PJ to 1582 PJ). Another driver is that the embodied energy flowing from overseas (industrial energy use activities) to intermediate economic activity in Australia and eventually to overseas final consumption had also increased from 645 PJ to 846 PJ. This increased intermediate embodied energy flowing through economy may indicate a growing role of Australia in global supply chains. In addition, the difference between the embodied energy use in the import and the export had widened, making Australia a greater net importer of embodied energy.

Considering a population growth of 17% between 2006 and 2015 (Australian Bureau of Statistics, 2017a), the growth of direct household energy use was moderate (13% increase, which is a 3% reduction on a per capita basis). The indirect energy use embodied in the household consumption of commodities increased by 25% (a 7% increase on a per capita basis), which was partly met by the sharp increase in imports. Total domestic demand that was satisfied by domestic industry energy use dropped from 49% to 41%, indicating an increasing outsourcing of energy use, and the associated GHG and air emissions impacts. For other final consumption, energy embodied in government consumption remained steady, while that of fixed capital formation increased, driven by foreign investment.

The drivers behind the change in the domestic embodied energy use (household consumption excluding direct household energy use + government consumption + fixed capital formation, the rightmost section of Fig. 6) are further explored by structural decomposition analysis in the next section.

3.3. Structural decomposition analysis of embodied energy

Structural decomposition analysis shows the contributions from six factors to the change in the total embodied energy use in Australia between 2006 and 2015 (EE in Fig. 5). Fig. 7(a) shows the cumulative change since 2006. As cumulative (period-wise) results are very sensitive to the choice of base year (Ma and Stern, 2008), year-by-year basis results are also included (Fig. 7(b)). For the period-wise result, population growth and per capita demand for imported commodities are two major contributors for the increased total embodied energy, which was partly offset by

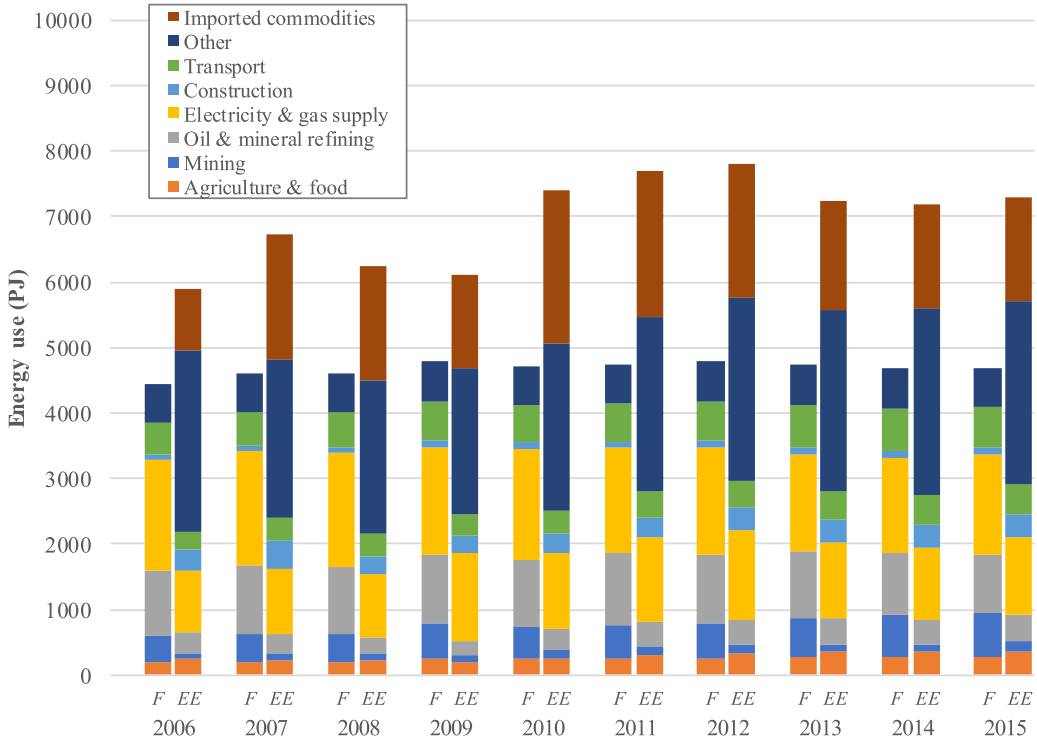

Fig. 5. Direct domestic energy use by industry (*F*) and embodied energy use in final domestic consumption (*EE*) between 2006 and 2015.

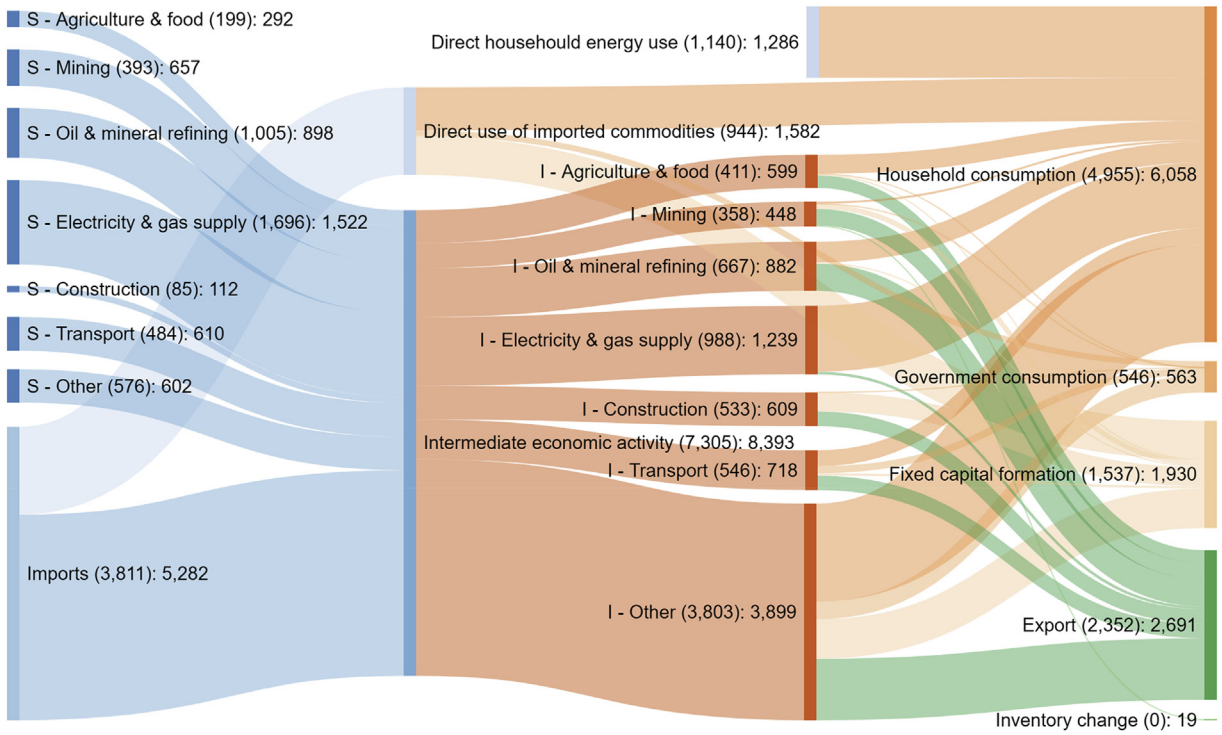
S - Agriculture & food (199): 292
S - Mining (393): 657
S - Oil & mineral refining (1,005): 898
S - Electricity & gas supply (1,696): 1,522
S - Construction (85): 112
S - Transport (484): 610
S - Other (576): 602
Imports (3,811): 5,282
Direct household energy use (1,140): 1,286
Direct use of imported commodities (944): 1,582
I - Agriculture & food (411): 599
I - Mining (358): 448
I - Oil & mineral refining (667): 882
I - Electricity & gas supply (988): 1,239
I - Construction (533): 609
Intermediate economic activity (7,305): 8,393
I - Transport (546): 718
I - Other (3,803): 3,899
Household consumption (4,955): 6,058
Government consumption (546): 563
Fixed capital formation (1,537): 1,930
Export (2,352): 2,691
Inventory change (0): 19

Fig. 6. Comparing energy flow between 2006 (in brackets) and 2015 (energy unit: PJ). The sum of the industry activity sources of energy use (S) is the direct domestic energy use by industry (*F*) in Fig. 5. The sum of household consumption (less direct household energy use), government consumption and fixed capital formation is the embodied energy use in final domestic consumption (*EE*) in Fig. 5.

overseas energy intensity reduction.

Consistently, population growth in Australia has contributed positively to its increasing total embodied energy use. Changes in economic structure (structural interdependencies between industry sectors) and per capita demand for imported commodity (affluence) had a bigger contribution to the changes in total

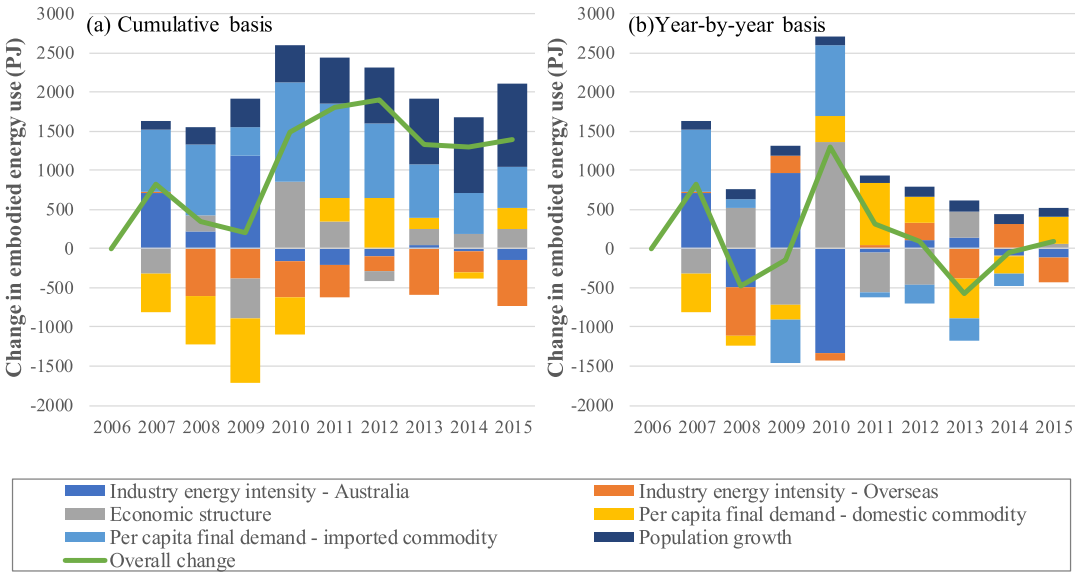

Fig. 7. Contribution of six factors to the change in total embodied energy use in final domestic consumption from 2006 to 2015. (a) Cumulative basis using 2006 as the base year; (b) Year-by-year basis comparing to the previous year.

embodied energy use on both cumulative and year-by-year basis. While there was an improvement in energy efficiency in domestic industries (i.e., a reduction in energy intensity), the overall contribution is relatively insignificant. On the other hand, overseas energy efficiency improvement seems to be making a greater contribution to offset other drivers that increased embodied energy use. The detailed decomposition results for the industry energy intensity factor (Australia) shows that its top contributor is the electricity supply sector.

3.4. Structural path analysis of embodied energy

Structural path analysis (SPA) can be performed to identify the top contributing paths to the total embodied energy use. Each path contains all the stages from the origin of industry energy use, to intermediate stages (except for direct industry supply to demand), to the final consumption of the commodity. Table 1 shows the top 10 paths for total embodied energy in Australia in 2006 and 2015. Because a supply-and-use table framework is used for Australia, a one-step path from electricity supply industry (Stage 1) to electricity supply commodity (Stage 0) represents a direct industry contribution to the embodied energy in the supplied commodity (electricity). With a symmetric IO structure for the rest of the world (RoW), the shortest path for imported commodity is one stage (Stage 0).

For both years, electricity supply, transportation sectors, and petroleum and chemical supply sectors dominated the top 10 contributing paths. In fact, electricity supply is the top contributing path for all the years between 2006 and 2015. The high total embodied energy in the electricity is predominantly the energy loss during thermal electricity generation. The paths from transportation sectors were becoming more significant. With some of the top paths being from overseas (ROW), it implies a need to improve the MRIO table by including key trading countries/regions as separate regions in the table in future work.

3.5. Implications for energy input-output analysis

The utilisation of net energy use vector in this study has avoided the double counting issue, which would arise with the use of gross energy use vector (Genty et al., 2012). The double counting occurs in energy conversion sectors such as petroleum refinery and electricity generation (e.g., the use of coal and natural gas for power generation, and the use of the generated electricity are both counted in the gross energy use view). For domestic industry energy consumption in Australia in 2015, the total net energy use was 4693 PJ, while the total gross energy use was 7910 PJ. With this difference, using the gross energy use vector would likely distort the results substantially.

While energy input-output analysis is arguably sensitive to the choice of the energy vector, the rationale and transparency of the energy vector used are not well discussed to our knowledge. Only in a recent study, Owen et al. (2017) compared the implications of using “energy-extracted” and “energy-used” vectors for consumption-based energy accounting. They also suggested that in their review, it is uncertain whether energy losses are accounted in those studies utilising “energy-used” vector. In this current study, the rationale for utilising the “energy-used” vector is because of the objective of investigating sectoral energy intensity changes. In addition, “energy losses” were allocated to the corresponding energy supply sectors.

In the literature, the domestic technology assumption is a popular approach to account for the embodied impact in import (Tukker et al., 2013). While this approach is popular for its simplicity of using only the national input-output data and environmental extensions, it can potentially compromise the quality of the results. In this study, the temporal results show an increased embodied energy import in the analysed period. This reinforces the trend of increasingly globalised supply chains. The trend also implies that it is essential to explicitly account for the embodied energy and other impacts in import in a national input-output analysis framework. This was achieved in this study by integrating the detailed nation supply-and-use table with a global input-output database. It could be a short-term approach as more globally harmonised environmental extensions becoming available for global input-output databases (Tukker et al., 2018).

While there are studies focusing on the embodied energy flow of specific energy products such as natural gas (Kan et al., 2019),

Table 1
Top 10 paths for total embodied energy in Australia in 2006 and 2015.

	Rank	Embodied energy, PJ (% of total)	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
2006	1	655 (10.37%)	AUS-COM Electricity Supply	AUS-IND Electricity Supply				
	2	170 (2.69%)	ROW Petroleum, Chemical and Non-Metallic Mineral Products					
	3	121 (1.91%)	AUS-COM Electricity Supply	AUS-IND Electricity Supply	AUS-COM Electricity Supply	AUS-IND Electricity Supply		
	4	80 (1.26%)	AUS-COM Petroleum and Coal Product Manufacturing	AUS-IND Petroleum and Coal Product Manufacturing				
	5	48 (0.75%)	ROW Petroleum, Chemical and Non-Metallic Mineral Products	ROW Petroleum, Chemical and Non-Metallic Mineral Products				
	6	47 (0.74%)	AUS-COM Road Transport	AUS-IND Road Transport				
	7	45 (0.72%)	AUS-COM Public Administration and Regulatory Services	AUS-IND Public Administration and Regulatory Services				
	8	39 (0.61%)	AUS-COM Finance	AUS-IND Finance	AUS-COM Electricity Supply	AUS-IND Electricity Supply		
	9	37 (0.58%)	AUS-COM Other Agriculture	AUS-IND Other Agriculture				
	10	30 (0.48%)	ROW Electrical and Machinery	ROW Petroleum, Chemical and Non-Metallic Mineral Products				
2015	1	711 (9.47%)	AUS-COM Electricity Supply	AUS-IND Electricity Supply				
	2	229 (3.06%)	AUS-COM Electricity Supply	AUS-IND Electricity Supply	AUS-COM Electricity Supply	AUS-IND Electricity Supply		
	3	120 (1.60%)	ROW Petroleum, Chemical and Non-Metallic Mineral Products					
	4	103 (1.37%)	ROW Transport					
	5	89 (1.18%)	AUS-COM Petroleum and Coal Product Manufacturing	AUS-IND - Petroleum and Coal Product Manufacturing				
	6	80 (1.06%)	AUS-COM Road Transport	AUS-IND - Road Transport				
	7	74 (0.99%)	AUS-COM Electricity Supply	AUS-IND Electricity Supply	AUS-COM Electricity Supply	AUS-IND Electricity Supply	AUS-COM Electricity Supply	AUS-IND Electricity Supply
	8	63 (0.84%)	ROW Electrical and Machinery					
	9	49 (0.65%)	AUS-COM Air and Space Transport	AUS-IND Air and Space Transport				
	10	43 (0.58%)	AUS-COM Sugar and Confectionery Manufacturing	AUS-IND Sugar and Confectionery Manufacturing				

Because a supply-and-use table framework is used for Australia, industry (AUS-IND) and commodity (AUS-COM) stages are explicitly distinguished. ROW refers to importing from overseas.

nuclear energy (Cortés-Borda et al., 2015), coal (Wu and Chen, 2018) and oil (Tang et al., 2012), few studies differentiated the total energy flow in term of different energy product sources in a single study. With the energy source details, one can better characterise the embodied energy-related GHG. While the analysis of the embodied energy by energy product sources in the final consumption is beyond the scope of this work, this information is present in the domestic energy extension used in this study (Fig. 3). Utilising this energy use by energy product source information can support carbon footprint accounting when the GHG account is too aggregated for input-output analysis. For instance, the Australian national GHG account (Australian Greenhouse Emissions Information System) has a 34 industry sector classification (Department of the Environment and Energy, 2018). The energy extension developed in this work (19 energy products by 110 industry sectors) can be used as a proxy to disaggregate the national GHG account for a higher resolution GHG input-output analysis.

3.6. Limitations

This study used annual expenditure data on 11-16 energy products by 109–114 input-output industry groups (from the supply-and-use tables by the ABS, the number of industry groups are not the same in all the years because of changes in industry classification) to disaggregate energy use of 22 sectoral groups (from the Energy Account, Australia by the ABS) into energy use of 110 input-output industry sectors. While the use of this monetary approach is a limitation, it provides a reasonable allocation of energy use to various sub-sectors within each aggregated sectoral group (Su et al., 2010). This is arguably better than allocating base on sectoral monetary output in some studies (Guo et al., 2018). More importantly, the disaggregation process enabled the use of the detailed national supply-and-use table for energy input-output analysis (110 industries and 110 commodities), instead of aggregating the industry sectors of the supply-and-use table into 22 sectors. Earlier works have shown that “preserving” the sectoral details for input-output analysis is generally preferred (Lenzen et al., 2004b; Steen-Olsen et al., 2014; Su et al., 2010).

This study used an aggregated rest of the world with 26 sectors for the input-output analysis, similar to that of Wiedmann et al. (2016) and Wolfram et al. (2016). This is a major limitation, considering that the overseas contribution to the embodied energy is not small according to results from SDA and SPA. With energy intensity being different across countries, having key trading countries/regions as separate regions in the MRIO table could be important. We acknowledge that some work have addressed this limitation (Owen et al., 2018; Sakai et al., 2017). As the input-output database platform used in this work is being extended to the global scale (Lenzen et al., 2017a), this limitation would be better addressed in future work.

4. Conclusions

Using a time-series set of national supply-and-use tables

integrated with a global input-output database, this study investigated the direct and indirect industry energy intensity and embodied energy flow in Australia between 2006 and 2015.

In 2015, only approximately half of the total embodied energy in final domestic consumption and export was physically used in Australia. The indirect household energy use through consumption of commodities was over three times that of direct household energy use. Consequently, improving end use energy efficiency should also consider the embodied energy in commodities. While Australia is a significant supplier and exporter of energy resources, analysing its embodied energy use flow provides a different perspective. The analysis shows that over the studied period, Australia was being a greater net energy use importer with energy embodied in the imports being double that of exports. This shows a significant outsourcing of energy use, and the associated GHG and air emissions impacts.

Between 2006 and 2015, there was an average annual 2% reduction of the national direct energy intensity, contributing strongly from the commercial and services industry and electricity supply sector. In contrast, primary industry and manufacturing groups (e.g., agriculture, food manufacturing) generally increased their direct energy intensity. Nearly all industry sectoral groups had reduced their total energy intensity because of direct energy intensity reduction from other or within industry sectoral groups. SDA shows that population growth and per capita demand for imported commodities are two major contributors for the increased total embodied energy. This increased total embodied energy was partly offset by the energy intensity reduction in the electricity supply sector.

Both SDA and SPA have shown an important role of the electricity supply sector in influencing embodied energy, and likely embodied energy-related GHG emissions. While Australia has reduced the share of coal for power generation in recent years, renewable energy sources (mostly from wind, solar and hydro) still only provide approximately 15% of the national electricity supply as of 2018. A future source of improvement for both direct and embodied energy would therefore be from phasing out coal-fired power generation (i.e., reducing primary energy input). In term of GHG accounting, the energy extension (with energy product information) developed in this study can be used in future work to improve the quantification of embodied energy-related GHG.

Acknowledgements

The authors acknowledge the funding support from the Australian Research Council Discovery Early Career Researcher Award (DE100101322).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.03.322.

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